High-Voltage Pulse Testing of Cables on Hawk*

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ABSTRACT

The Hawk facility at NRL was used to pulse test Dielectric Sciences[1] 2158 cable to voltages in excess of 900 kV. The motivation for the testing was to assess the utility of these cables to connect elements in a high-impedance inductive voltage adder system. A high voltage pulse was launched at both ends of a long length of cable to obtain high voltage by wave adding in the middle of the cable while limiting high voltage complications at the power feeds to the cables. The pulse width was controlled with a point-plane electron beam diode.

Extensive modeling was used to design and analyze the experiment. Potential plotting was employed to design the field shapers used to connect the outer conductor of the cable to the power feeds, and verify that we could expect to achieve appropriately high voltage on the cables. The initial impedance of the point-plane diode was modeled with the MAGIC PIC code. A transmission-line code was used to model the overall circuit and infer the voltage in the cable as a function of position and time.

Four lengths of cable were tested. The cable is designed for use as 69 kV AC power cable. Three of the four cables survived pulses in excess of 900 kV before failing, and the fourth cable failed at over 700 kV. Extensive results of the tests on the 2158 cables will be presented.

I. INTRODUCTION

High-voltage, solid-dielectric cables are standard equipment in the power transmission industry. There was a desire to quickly assess the potential utility of these cables for connecting pulse-forming networks to inductive cavities in a high-impedance system. The basic dimensions of the cables suggest that the 69-kV AC power cables could be used at over 500 kV in pulsed duty. The task at hand was to quickly determine the voltage breakdown limits of the bulk cable, without having to build a dedicated pulser or be limited by breakdown limits at the cable connectors. The solution we arrived at was to use transit time wave-adding in long cable lengths.

The HAWK generator[2] is used primarily for testing various vacuum opening switch systems. It consists of 4 parallel sub-Marx units. Since the cable testing requires primarily voltage and not current, we used one sub-Marx to generate the voltage pulses we injected onto the cable. The simplified schematic of the circuit is shown in Fig. 1.

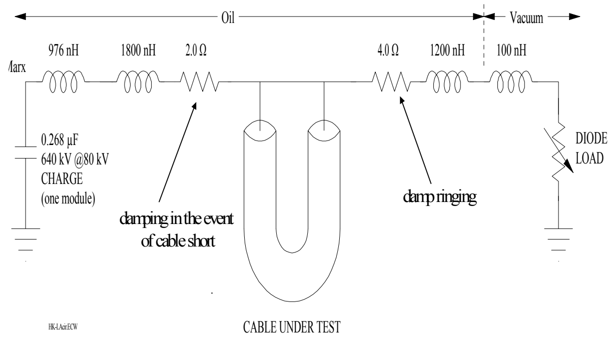

Figure 1: Schematic of HAWK cable test circuit.

A key element in the circuit was the diode load. The desired behavior of the load was an initial impedance much larger than the 25 Ω effective impedance of the cable, and then swiftly transition to zero impedance after enough time had passed for the waves to add in the cable. The 2-Ω resistor between the Marx and cable was needed to limit the current and dissipate energy in the event of a cable failure. The 4-Ω resistor between the cable and the diode load was needed to dissipate energy and damp transients after the diode load shorts out.

II. Point-Plane Diode

The diode load we used was a point-plane diode. The cathode was small diameter tungsten rod, and the anode a uniform plane. The principle behind this load was that the impedance of the e-beam diode would be high, and fairly constant for most diode gaps, then plasma closure would occur after a time set by the initial gap spacing.

The diode was simulated using the MAGIC 2-D PIC code[3]. The cathode was a 2-mm diameter rod. Electron emission occurred at over 300 kV/cm. The voltage was fixed at 1.5 MV. Ion emission was optional, and when it was allowed, it came from regions that had electron bombardment. Figure 2 shows the results of the simulation. Figure 2a shows electron orbits at 10 ns. Figure 2b shows the calculated diode impedance as a function of the anode-cathode gap, with and without ion emission. Note that the electron current is dominated by emission from the shank, which is insensitive to the anode-cathode gap spacing.

The point-plane-diode was implemented with a 3.2-mm diameter tungsten cathode and a 14-mm diameter

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14. ABSTRACT

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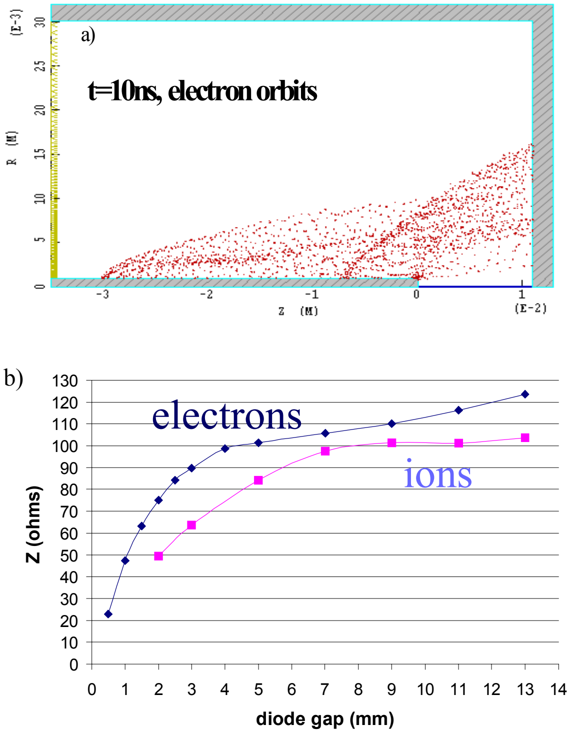

Figure 2: a) Electron orbits in point-plane diode. b) Calculated diode impedance with and without ions.

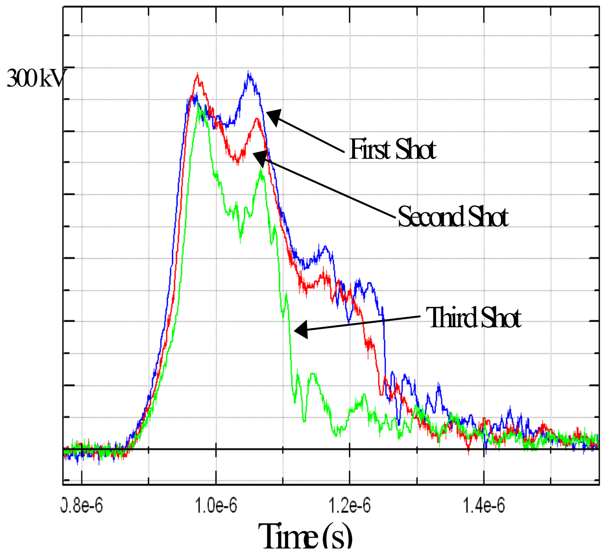

Figure 3: Diode voltage on 3 sequential shots with a 14-mm gap and 40 kV Marx charge.

stainless steel anode button. The gap between the hub and door surface was over 4 cm, so the point-plane gap dominated the impedance of the vacuum section. Surfaces of the electrodes external to the anode-cathode gap were coated with diffusion pump oil to help suppress electron emission from regions other than the point-plane gap.

Figure 3 shows the voltage across the diode gap, on 3 successive shots with a 14-mm gap and a 40-kV Marx charge. No maintenance was performed between shots, and no cable was installed for testing. The voltage was measured with a capacitive voltage divider at the oil-vacuum interface. The amplitude and duration of the voltage pulse proved to be a cleaner indicator of the performance of the point-plane diode than the impedance. The amplitude of the voltage pulse and the pulse duration of the high impedance phase decrease with each successive pulse, to an unacceptable level after 3 to 4 shots. The original performance is restored by cleaning and re-oiling the surfaces. The impedance during the high voltage phase is about 100-125 ohms, consistent with the simulations.

III. Cable Connections

The final critical element in the assembly is the field shaper at the outer conductor of the cable where it is connected to the ground of the Marx. The concern at this connection is to minimize the enhancement of the electric field over the field in the cable, in order to prevent breakdowns in the cable dielectric or in the oil fill around the cable dielectric. The field shaper was constructed with a 3.75-cm radius, which limited the field enhancement over the field in the cable. In negative polarity (cable center conductor at negative high voltage) and a voltage of 500 kV and an effective time of 300 ns, the field would be 65% of the JCM breakdown, while in positive polarity, the field would be 43% of JCM breakdown. During cable testing, failures were at 450 kV at the connector in negative polarity, while voltages in excess of 550 kV caused no breakdowns in positive polarity. Positive polarity was used for most of the cable testing.

IV. Cable Testing Method and Analysis

Both ends of an approximately 50-m length of DS 2158 cable were connected to a common point in the Marx oil tank. The bulk length of the cable was suspended above the Marx tank. A voltage divider was connected at the connection of the cables to the Marx and two Rogowski loops monitored the current into each end of the cable. The BERTHA transmission line code[4] was used to model the circuit and determine the distribution of voltage in space and time in the cable.

Figure 4a shows the measured and calculated voltages and currents at the inputs to the cable, for a shot with an 11-mm diode gap and 65 kV Marx charge (shot 3190). For these conditions, the point-plane diode closes after the full transit time of the cable, and prevents the Marx from ringing the voltage up on the lower capacitance of the cable. Figure 4b shows the voltages calculated at various locations in the cable. V_{mid} is at the center of the cable, $V_{1/3}$ is at 1/3 of the cable length from the connectors (closer to the middle than the ends), and $V_{1/6}$ is at 1/6 of the cable length from the connectors (closer to the ends than the middle). Note that the voltage at the end of the cable is doubled at the middle of the cable, and nearly

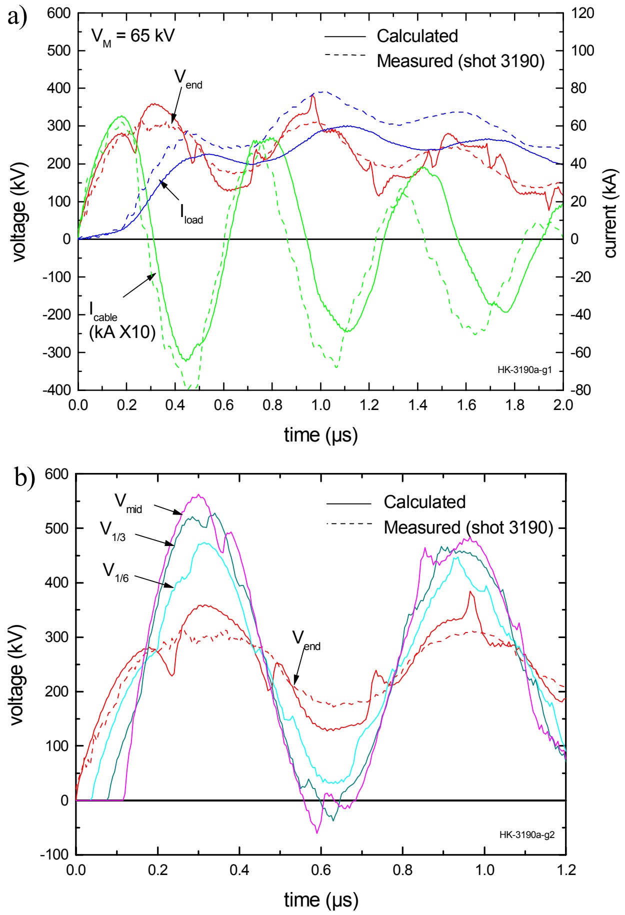

Figure 4: Measured and calculated voltages at cable end for an 11-mm diode gap and 65 kV Marx charge. b) Voltage distribution along test cable.

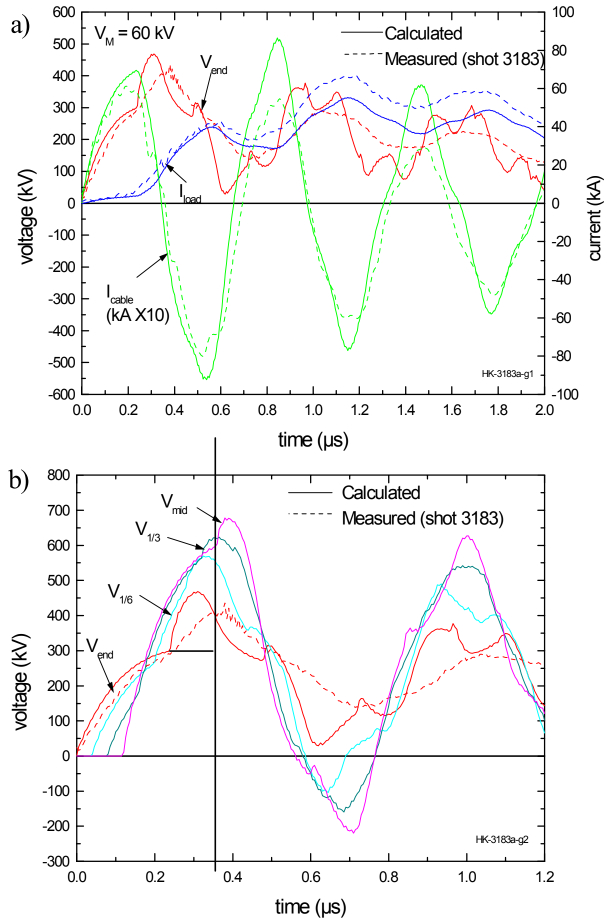

Figure 5: a) Measured and calculated voltages and currents at cable end for an 18-mm diode gap and 60 kV Marx charge. b) Voltage distribution along test cable.

doubled for the 1/3 of the cable length near the center of the cable.

Figure 5 shows similar data for an 18-mm diode gap and a 60 kV Marx charge. In this case, the point-plane diode does not close until after the one-way transit time of the cable, and the Marx sees the cable as a charged capacitor, and not a 25-Ω load. The increase in voltage later in time at the cable input is due to C-L-C ringup. However, this increase in voltage at the cable input does not get doubled in the middle cable. This mode of operation was judged to be undesirable, as it generates much higher voltage at the cable connectors, where breakdowns could occur at the field shaper, without testing the bulk of the cable at a higher voltage. Most test shots were taken with conditions similar to those in Figure 4.

V. Cable Breakdown Analysis

A total of 120 shots were put on 4 different lengths of DS 2158 cable. The point-plane diode was maintained every three to four shots, giving a range of voltages on the cable, for nominally the same settings. Three cables survived voltages in excess of 850 kV, before failing on subsequent pulses. The punctures on those three cables were in the center third of the cable, where the transit-time voltage double occurs. The fourth cable failed at a peak voltage on 730 kV, but the failure was closer to the cable end. A defect in the cable, from either manufacture or handling, is suspected in this case.

The first cable had the most pulses applied, as the Marx voltage was slowly increased to find the cable limits. A total of sixty nine pulses were applied. The cable failed on a shot with a peak voltage in the center of the cable of 860 kV, where six of the seven preceding pulses were above 850 kV, with three at 930 kV. The second cable failed at a peak voltage of 740 kV, after surviving 960 kV in the previous pulse, and three pulses above 850 kV before that. The third cable failed at 920 kV, with eleven previous shots above 850 kV, including three from 910 to 920 kV.

The useful voltage for these cables would appear to be in excess of 750 kV, given that the one low voltage failure of a cable could be ascribed to manufacturing defects or handling damage.. The test setup on HAWK produced substantial ringing of voltage and current on the cables,

and actual testing with the voltage and current histories of the real application would be recommended to determine the useful voltage limits for these cables.

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** JAYCOR, Inc, McClean VA

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